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LIQUID PROPELLANTS IN GUNS

A Thesis

Presented to the Faculty of the Graduate School of
Cornell University for the degree of
Master of Science in Engineering

By
Arlie George Capps

September 1948

RESTRICTED

Biography

Arlie George Capps was born in Jefferson City, Missouri, August 8, 1918. He attended the University Elementary and High Schools in Columbia, Missouri, and completed two years of college at the University of Missouri before receiving an appointment in 1937 to the United States Naval Academy. He graduated from the Naval Academy on February 7, 1941, with the degree of Bachelor of Science and a commission as Ensign in the United States Navy. His first duty assignment was aboard a Pacific Fleet destroyer where he soon began specialization in radar and gunnery. He spent the next five years closely associated with gunnery and radar problems of destroyers at war. At the close of the war he was ordered to the Post Graduate School, U. S. Naval Academy, for a three year course of study in Ordnance Engineering. After one year at the Post Graduate school, he was ordered to Cornell University in September, 1946, for the purpose of completing that course of study.

[illegible]

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Introduction

A real problem of every gunnery officer afloat is the handling of ammunition during action and even during peace. Especially during action, when time and manpower are most precious, the factors causing cumbersome handling methods come up for his close scrutiny. Thus from his entirely practical survey, the proposal to use liquid instead of solid propellants for the purpose of easing the shortage of time and manpower in ammunition handling looks attractive. The idea is not new, but very little has been done toward investigating and evaluating the possibility of using liquid propellants for guns.

Liquid propellants may help solve other gunnery problems as well as the handling problem. Scientific methods are being adopted rapidly in every phase of gunnery, but the transformation of gunnery from an art into a science is only partially complete. Tactical demands for higher rates of fire at higher velocities are far ahead of the ability of practical gunnery to meet such demands. The propellant, both physically and chemically, may be the field where scientific study should be undertaken next. Much basic research in solid propellants is being done, but little has been started in the field of liquid propellants for guns.

The objects of this thesis are 1) to define and outline the requirements of the gun-propellant system and 2) to illustrate by specific application some problems arising with the use of liquid propellants. That the propellant handling phase may not be the only place in gunnery where improvement could be made through the use of a liquid propellant will be emphasized. There is no intention of implying that the liquid propellant would be a cure-all for practical gunnery problems, but it is believed that improvements are necessary and that here is a field that looks promising. Since most of the related experimental data are classified, only the general problem will be outlined here in such a way that its essential features will be made apparent to any reader wishing to undertake critical study in this field.

Part I. Requirements of a Gun-Propellant System

Section I. 1. Basic Concepts

A gun is simply a means to an end - that of imparting a desired velocity to an object. However, the requirements of high velocity, mechanical flexibility in elevation and train, and rapidity of fire make the modern gun an enormously complicated machine. One of the major practical limitations in operating this machine is that of maintaining the supply of projectiles and propellant to the gun during prolonged firing. The gun is necessarily a "batch process" is so far as the projectile is concerned, but the question arises as to where the batch process should start for the propellant. If a "flow process" could be employed for the propellant up to the final stage of proportioning it into the gun, it appears that a great improvement in handling efficiency could be realized. A liquid propellant may make possible such a flow process.

Some definitions are needed before looking at the problem more closely. These definitions are very broad so that ideas of conventional design and usage will not limit or prejudice the development of this new subject. The term gun is used to specify a special type of heat engine designed to convert the stored-up chemical energy of a propellant into kinetic energy of a one-stroke piston. In order to accomplish this conversion of energy the propellant is converted in the chamber (cylinder) into high pressure gases which act by expansion to impart velocity to the piston. This piston may be a "free piston" as is the case when the gun fires a projectile or rocket directly. However, as employed in the catapult the piston may be merely a vehicle used to transmit the velocity to the prime object, for instance an airplane or rocket. From this definition and in terms of modern heat engines the liquid fuel certainly seems plausible.

A propellant is a chemical system capable of decomposition into gases at a rapid but controllable and reproducible rate. Once again this definition permits us to consider liquids as well as solids, although there may be need to investigate entirely new control methods in order to obtain the desired rate of gas evolution. In gunnery, at the present, the term propellant is rarely heard. Powder is the descriptive word found in common usage in such terms as "powder hoist", "powder case" and "powder bag". The powder idea is a carry-over from the days of black powder which was initially a fine, granular charcoal powder. Today's gun propellants are rarely powders but are instead solids of definite size and shape, designed to give a specific surface as a means of controlling the rate of gas production. The real question is whether the propellants need to be solids.

The term liquid is difficult to define critically, but for the purpose of this paper a liquid is any material that can be readily handled at room temperatures (plus or minus about 100°F) by such methods as pumping, pouring, and atomizing. Examples of such liquids are gasoline, benzene, and liquid hydrogen peroxide.

Section I 2. Particular Requirements.

The basic concepts above were stated for the purpose of permitting the broadest possible interpretation of the gun-propellant system. However, specific requirements must be introduced before any practical system can be investigated and evaluated.

Consider some gun requirements. As the speed of the target is increased there is a certain point where a gun of a given muzzle velocity becomes useless against the target. Tomorrows targets will certainly travel at nearsonic or super-sonic speeds and gun defense tactics against such targets will dictate the highest possible muzzle velocity, held within limits by the maximum allowable pressure in the gun. The need for high velocity sets definite requirements for the propellant at the same time. More propellant energy per pound of projectile is required for higher velocities. But the propellant must do expansion work to impart velocity to its own weight as well as the projectile weight. To keep this non-useful work at a low relative value, high energy content per pound of propellant is desirable. Returning to gun requirements, long life which depends on minimizing erosion of the barrel caused by burning away of the metal by the hot gases, is a very important requirement that is especially hard to meet in rapid-fire guns. Flexibility, already mentioned, must be accompanied by ease of servicing, simplicity of design, ease of loading, and perhaps most of all reproducibility of fire. Not every gun will have these requirements to the same degree, consider a catapult for instance, but evaluation of any gun-propellant system should consider these points among others.

A typical list of specific requirements for solid propellants is:

1. Stability during storage.

2. Ability to withstand exposure to extreme temperatures (approximately 400°F) for a short period as in case of a misfire in a hot gun.
3. Progressive burning.
4. High energy content per unit weight.
5. Non-sensitivity to shock.
6. Non-detonating.
7. Relatively easy and safe to handle.
8. Not excessively erosive to the gun.
9. Relatively easy to ignite.
10. Smokeless.
11. Flashless.
12. Reproducible ballistically.
13. Free from excessive corrections for initial temperature.
14. Adaptable to securing of a simple, effective gas seal in the gun.
15. Adaptable to rapid fire.
16. Be operable at -40°F.
17. Can be made available in large quantities in time of emergency.

A list of specific requirements for a liquid propellant need not include all of the above requirements, but many are intrinsically required of any propellant used in guns.

Specific requirements for a liquid will have to be set up when more is known of the high pressure behavior of liquid propellants. The viscosity limits must be set, for instance.

Section I 3. Need for Fundamental Research.

Solid gun propellants have been in use for over 100 years during which time very little thought has been given to the possible use of liquids as propellants. The reason for staying with the solids is that they have been perfected to a high degree and have proved entirely satisfactory in the applications in which they were needed and used. In fact, the emphasis in gunnery development in the past 20 yeats has been on bringing the performance of fire-control equipment up to the standards of gun performance. It is my belief that the emphasis should now be placed on the performance of the gun itself, and that improvements are needed for the following reasons:

1. Muzzle velocities are too low.
2. Gun life is too short
3. Storage problems limit the firing capacity.
4. Too many men are needed to handle the ammunition, hence for any given size of ship or tank, the number of guns firing is definitely limited by the inability of the

vessel to carry sufficient manpower to keep more guns firing simultaneously.

It is possible that the consideration of liquid propellants may indicate how to remove most, if not all, of these major limitations on gun performance. The nature of these problems must be analyzed and then the sciences must be called upon to study the clearly defined components. Specifically chemistry, physics, and engineering design elements must be sorted out, then basic research must be initiated in these fields.

The research in chemistry should aim at development of liquid propellants with:

1. Low adiabatic flame temperature to give less gun erosion.

2. Explosion products of low molecular weight in order to give better gun efficiency at super-velocity.

3. Suitable stability when subjected to high pressure and shock.

4. Suitable viscosity.

The physics problems are related to interior ballistics. Research in physics should aim at development of:

1. Methods of controlling burning rates.

2. Methods of injection or other suitable means for getting the propellant into the gun.

3. Methods of computing the pressure, volume displacement, and power required to deliver the propellant to the gun at the correct rate.

4. Methods of computing velocity-displacement relations.

Finally, satisfactory engineering designs must be developed for the gun-propellant system considering practical requirements of:

1. Serviceability.
2. Safety features.
3. Flexibility.
4. Minimizing the number of operating personnel.

It is evident that the results of these studies must be closely co-ordinated by a group familiar with the future tactical requirements of the gun.

Part II. Problems Connected with Liquid Propellants.

Section II. 1. General Characteristics of Liquid Propellants.

Liquid propellants may be classified by their number of components, for instance one and two component propellants are termed mono-propellants and bipropellants. An advantage of the bi-propellant is that two relatively stable compounds can be handled and stored separately with safety, each being non-explosive until mixed with the other. This feature, however, may be a disadvantage in those applications where unintentional mixing through container damage may occur as on board ships and in tanks. Another disadvantage of the bi-propellant is the relatively long time required for mixing which may make the overall reaction time excessive. Still another expected disadvantage of the bipropellant is further complicated of injection machinery. The advantage of the mono-propellant is that it can be handled quickly and simply, however, most mono-propellants have the disadvantage of relatively low shock and temperature stability. Nevertheless, at the present, the mono-propellant appears to be the better choice for investigation.

Application of liquid propellants has been largely restricted to rockets and jet-propelled aircraft and missiles where the pressures encountered are but a fraction of those to be expected in guns or even catapults. A typical liquid propellant rocket chamber pressure is 300 p.s.i.. This pressure factor of more than 100 eliminates the direct application of many known liquid propellants in guns because of their ease of detonation at high pressure. Some of the results of research in liquid propellants for rockets could be utilized to obtain properties needed for the study of gun application. As an example, the characteristic chamber length, L^+, which is determined for propellants used in rockets, is related to the reaction rate which must be determined for propellants used in guns.

Section II 2. Specific Characteristics Applied to Le Duc Interior Ballistics Formulas.

In what way the physical qualities of the propellant enter the gun performance may be seen by studying interior ballistics. In 1926, Cranz, one of Germany's leading ballisticians, said of this subject,[1] "It would be an ideal situation if, once the gun, the projectile, the weight of powder charge, and the physical and chemical properties of the powder are known, we could determine by a purely theoretical procedure the time variation of the gas pressure in the barrel, and the gas temperature. However, in consequence of the great complexity of the problem and the lack of empirical ground work, we shall find interior ballistics so far from this ideal that it may be said to be still in the rudimentary stages of its development." Although there have been improvements during the past 20 years, the subject is still filled with semi-empirical formulas. Since no empirical data are available as yet for the behavior of liquid propellants in guns, it is my plan to modify the simplest satisfactory solid propellant ballistic treatment insofar as it seems permissible, indicating all assumptions and what is lacking by such procedure. In this manner the importance of some qualities of propellants can be clearly seen.

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[1] Cranz's Textbook of Ballistics. Vol. II Part I

The Le Duc Formulas (with modifications)

The French ballistician, Le Duc, originally derived a set of semi-empirical interior ballistic formulas from experiments for calculating recoil pressures. These formulas were later modified for American powders and adopted as standard for U.S. Naval Proving Ground interior ballistic problems. The following derivation is condensed from the treatment given in Naval Ordnance 1939, and modification of coefficients and constants will be made for 90% hydrogen peroxide as the propellant. Hydrogen peroxide is chosen because it has been widely investigated and is unclassified. It was successfully used by the Germans in the catapult launcher for the V-1 buzz bomb. This launcher operated with a chamber pressure of about 800 p.s.i. behind a piston in a "cannon", 11.5-inches inside diameter and 160 feet long.[1]

The physical characteristics of 90% hydrogen peroxide which interests us here are[2]

1. Heat of decomposition of approximately 1100 BTU/lb.
2. Adiabatic flame temperature of approximately 1570°F at 10,000 p.s.i..
3. Specific gravity of 1.39 at 64°F.
4. Viscosity 0.0130 poises at 64°F.
5. Critical temperature 858°F.
6. Non-detonating when uncontaminated.

Now let us proceed with the derivation of Le Duc's formulas modified for 90% H_2O_2. A relationship between velocity and travel of the projectile in the bore is assumed from the results of experiments for calculating recoil pressures. This approximate relationship is theoretically true for slow degressive powders only[3], however, because of its simplicity it has been used in gun-design work for many years, giving fairly good approximations of pressure and muzzle velocity under many conditions. In the case of the 16 inch 45-caliber gun, the powder charge and the maximum pressure, computed before the gun was built, were on actual firing found to be very nearly exact.[1]

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[1] Industrial and Engineering Chemistry - February 1946

[2] Properties of Becco Hydrogen Peroxide - 1946

[3] Ordnance and Gunnery - Tschappat

The assumed relationship between velocity and projectile travel is given by the equation

1) $$v = \frac{a\,x}{b+x} \quad , \text{ or } \quad \frac{a}{(b/x)+1}$$

where v = velocity, ft. per second,

x = projectile travel in the bore, feet,

a,b = constants.

Letting x become infinite, $v = a$. From this is is seen that a is the velocity that the projectile would have if all the available energy of the propellant charge were converted into projectile velocity in the gun. The total work done by the gases would equal the kinetic energy of the projectile.

For kinetic energy we have

$$\text{K.E.} = \frac{w\,a^2}{2g} \text{ foot pounds}$$

where w = weight of projectile, pounds,

g = conversion factor, 32.2 ft/sec^2.

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[1] Naval Ordnance 1939 page 50.

Assuming adiabatic expansion of an ideal gas,

$$pV^n = \text{constant} = k$$

where

p = pressure, lbs/in^2.

V = volume, in.^{3}

n = ratio of specific heats.

The work done in expanding the gas from V_1 to V_2 is

$$W = \int_{V_1}^{V_2} pdV = k \int_{V_1}^{V_2} \frac{dV}{V^n}$$

$$= \frac{K}{n^{-1}} \left[\frac{1}{V_1^{n-1}} - \frac{1}{V_2^{n-1}}\right]$$

and when V_2 is infinite

$$W_{V_1} = \frac{K}{n^{-1}} \times \frac{1}{V_1^{n-1}}$$

Let E equal the work done by 1 pound of gas in expanding from V_1 which it occupies at unit-density[1] to infinity. Here V_1 is 27.68 cubic inches (i.e., the volume of 1 pound of water).

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[1] Note that unit-density is defined to make density numerically equal to specific gravity

Substituting we get

$$E = \frac{k}{n^{-1}} \times \frac{1}{(27.68)^{n-1}}$$

But if the expansion is from a density Δ instead of unit-density, then

$$V_1 = \frac{27.68}{\Delta}$$, and the work will be

$$W = \frac{K}{n-1} \times \frac{n-1}{(27.68)^{n-1}} = E\Delta^{n-1}$$

This is the work per pound of gas. For a charge of $\bar{w}$ pounds of propellant the total work is $W\bar{w}$ or $\bar{w}E\Delta^{(n-1)}$ which must equal the energy of the projectile, or

$$\frac{w\,a^2}{2g} = \bar{w}\,E\,\Delta^{n-1}$$

giving $a^2 = 2gE\,(\bar{w}/w)\ \Delta^{n-1}$

$$a = 2gE\ (\bar{w}/w)^{1/2}\ \Delta^{\frac{n-1}{2}}$$

The available energy per pound of 90% H_2O_2 is approximately 1100 BTU = 855,800 foot pounds

Hence,

$$\sqrt{2gE} = 7440$$

But owing to losses through heating the gun, forcing pressures to start the shell, friction, etc., we can use only 70%[1] of this value or 5230. The exponent n is C_p/C_v, the ratio of specific heat of the gases at constant pressure to that at constant volume, which is temperature dependent. However, an average value[2] of 1.24 is assumed as constant for the working temperature range. Then we get as an expression for the value of the constant a,

$$a = 5230\ (\bar{w}/w)^{1/2}\ \Delta^{(.12)}$$

Now we evaluate the constant b of the velocity equation. First it will be noted that b must have the dimensions of distance and it will be shown that b is related to the value of x, projectile travel, at the point of maximum pressure.

Writing the velocity equation as

$$bv + xv = a\,x$$

---

[1] At the Naval Proving Ground it was found that for a certain nitrocellulose powder $\sqrt{2gE} = 9706$. In order to make calculated values agree with firing results a value of 6823 was chosen, instead of 9706, the computed value of $\sqrt{2gE}$ for the certain powder. The ratio 6823/9706 was used to obtain 70%.

[2] Extrapolated from data in pamphlet entitled Becco Hydrogen Peroxide.

and differentiating with respect to time we get

$$(b+x)\,\frac{dv}{dt} = (a-v)\,\frac{dx}{dt}$$

substituting v from (1) we get

$$\frac{dv}{dt} = \frac{ab}{(b+x)^2}\,\frac{dx}{dt} = \frac{ab}{(b+x)^2}\,v$$

or

$$3)\qquad \alpha = \frac{dv}{dt} = \frac{ab}{(b+x)^2}\,\frac{ax}{(b+x)} = \frac{a^2bx}{(b+x)^3}$$

This is the expression for acceleration. It is assumed that the acceleration of the projectile follows the pressure curve. In other words, the maximum pressure occurs when the rate of change of the acceleration is zero. This is expressed by

$$\frac{d^2v}{dt^2} = 0$$

$$\text{or}\quad \frac{d^2v}{dt^2} = \frac{(b+x)^3a^2b-3a^2bx(b+x)^2}{(b+x)^6}\,\frac{dx}{dt} = 0$$

$$= \frac{a^2b(b-2x)}{(b+x)^4}\,\frac{dx}{dt} = 0$$

Since the factors $\frac{dx}{dt}$, $(b+x)^4$, and $a^2 b$ must be finite,

$$4) \quad b - 2x = 0 \, , \quad \text{or} \quad b = 2x,$$

showing that b is twice the travel of the projectile to the point maximum pressure.

Now let us analyze what factors determine the point of maximum pressure in the gun. For solid propellants a powder constant, β, is determined for every lot of powder which designates the relative "quickness" of the powder. The value of β depends on the web thickness, the grain shape and size, percentage of volatiles remaining, etc.. It is actually an index of the rate of burning under specific conditions. For slower burning powders the value of β is larger. The point of maximum pressure for solid propellants is also dependent on the amount of initial air space around the charge, occurring sooner for a small air space. It is a function of the weight of the projectile, too. An empirical expression[1] for b is

$$b = \beta\left(1 - \frac{\Delta}{\delta}\right)(S/W)^{2/3}$$

where

β = powder constant

Δ = density of loading

---

[1] *Naval Ordnance* 1939 page 54

δ = specific gravity of powder

S = chamber volume

W = weight of projectile

For the liquid propellant the determination of the burning rate will require study with various parameters such as mixing methods, atomization, injection rate, etc.. This is a field for basic research. For the moment we shall assume that this work has been done and that by one method or another a value of x for the point of maximum pressure can be obtained for the solid propellant. This would permit us to use our gun barrels of present design. Hence the treatment here will assume a suitable value for b depending on the gun only.

It is now possible to write a general expression for the pressure at any point in terms of the velocity constants. Starting with

$$\text{Pressure} = \frac{F}{A} = \frac{ma}{A} = \frac{wa}{gA}$$

where

F = force acting on base of projectile, lbs.

A = area of base of shell, in.^{2}

w = weight of shell, lbs.

g = conversion factor, 32.2 ft/sec^2

a = acceleration, ft/sec^2

then

$$P = \frac{w}{g} \; \frac{a^2bx}{A(b+x)^3}.$$

This expression, however, assumes that the pressure does only useful work. To correct for non-useful work the Naval Proving Ground found that multiplying the theoretical pressure by 1.12 gave good agreement with gauge pressures. Hence for maximum pressure

$$P_{\substack{max.\\ guage}} = 1.12 \text{ P max.}$$

and substituting x = b/2 we get

$$5) \qquad P_{\substack{max.\\ guage}} = \frac{1.12wab^2}{2g(3b/2)^3} \cong \frac{wa^2}{6gAb} \qquad \text{lbs/in}^2$$

There is still one factor to examine more closely, namely the density of loading, Δ, in the formula for determining a. This term, density of loading, must be interpreted for our liquid propellant. For the solid propellant Δ is the ratio of the weight of the powder charge to the weight of a volume of water, at standard conditions, sufficient to fill the volume S, of the powder chamber. Expressing S in cubic inches, this weight of water is $\frac{S}{27.68}$

and if $\bar{w}$ is the weight of the charge in pounds, then

$$\Delta = \frac{27.68\bar{w}}{S}$$

and $a = 5230\ (\bar{w}/w)^{1/2}\ (27.68\bar{w}/S)^{.12}$

This formula assumes that the total charge $\bar{w}$ is in the chamber when the burning takes place. Then Δ is the density that the charge would have if it entirely filled the powder chamber, which it would do if it were entirely converted to gases. Hence, Δ is a parameter related to the density of the gas under decomposition conditions of high temperature and pressure. For our liquid propellant this will be a function of the rate of injection and rate of burning.

Now it is assumed that the rate of injection can be correlated with the burning rate to give a value of Δ for the liquid comparable to that of the solid propellant. Certainly more convenient parameters involving rate of injection could be set up, but with the above assumption we can compute a value of a to match a particular gun-propellant system.

Summary of Formulas

Equations:

1) $v = \frac{ax}{b+x}$

2) $a = 5230\ (\bar{w}/w)^{1/2}\ \Delta^{(.12)}$

3) $\alpha = \frac{dv}{dt} = \frac{a^2bx}{(b+x)^3}$

4) $b = \frac{x}{2}$ (chosen to match gun)

5) $P_{max} = \frac{w\ a^2}{6gAb}$

6) $P = \frac{1.12\ w\ a^2bx}{gA(b+x)^3}$

Summary of Symbols

v = velocity, ft/sec.

a, b = constants

x = travel of projectile in bore, feet

P = pressure, lbs/in^2

S = chamber volume, in.^{3}

A = area of base of projectile (piston) in^2

$\bar{w}$ = weight of propellant charge, lbs.

w = weight of projectile (gross mass to be accelerated), lbs.

Δ = density of loading, ratio

g = conversion factor, 32.2 ft/sec^2

α = acceleration of projectile, ft/sec^2

t = time, seconds

Section II 3. Application of Formulas in Type Problems.

Thus far no specific gun has been introduced. In order to illustrate how the propellant characteristics affect the gun performance, we shall apply the ballistic formulas just derived for 90% hydrogen peroxide to three sets of specifications for guns (or catapults) with widely different parameters. The guns chosen are either unclassified or hypothetical and will serve only to give definite data with which to work.

Specifications A -

Gross weight to be accelerated	25,000 lbs.
End Speed	522 knots
Maximum pressure	6000-10,000 p.s.i.
Cylinder diameter	14 in.
Maximum acceleration	50 g.
Length	as necessary
Propellant	90% H_2O_2
Weight of charge	as necessary

From our formulas we can find an expression for $\bar{w}$, the weight of charge. The maximum acceleration is to be 50 g. or 1610 ft/sec.^{2} which will occur at $x = b/2$. then substituting in equation 3)

$$1610 = \frac{a^2 b\ b}{2(b+b/2)^3} = \frac{a^2 b^2}{2(3/2b)^3} = \frac{4a^2}{27b}$$

and substituting equation 2) for a, we get

$$1610 = \frac{4\ (5230)^2\ \bar{w}}{27b\ \ 25{,}000}\ \Delta^{.24}$$

$$\text{or} \quad \bar{w} = \frac{1610 \times 27 \times 25{,}000}{4 \times (5230)^2}\ \frac{b}{\Delta^{.24}}$$

$$\bar{w} = 10\ b/\Delta^{.24}$$

Also from equation 5)

$$P = \frac{w\ a^2}{6gAb} = \frac{\cancel{w}(5230)^2\ \bar{w}/\cancel{w}}{6gAb}\ \Delta^{.24}$$

$$= \frac{(5230)^2\ \bar{w}\ \Delta^{.24} \times 10}{6gA\ \ \bar{w}\ \Delta^{.24}} = \frac{(5230)^2 \times 10}{6g \times 49\ \pi}$$

= 9200 p.s.i. (this is within specifications)

We still have to determine a suitable powder charge and length of gun. Using end velocity as given,

$$v_e = 522 \text{ knots} = 522 \times \frac{10}{6} \text{ ft/sec.}$$

$$= 870 \text{ ft/sec.}$$

and setting it in the velocity equation, 1)

$$870 = \frac{a\,x}{(b+x)} = \frac{5230(\bar{w}/w)^{1/2}\,\Delta^{.12}\,x}{(b+x)}$$

Now assuming b = 100 ft, making $\bar{w} = \frac{1000}{\Delta^{.24}}$, gives

$$870 = \frac{5230(1000/\Delta^{.24})^{1/2}\,\Delta^{.12}\,x}{(100+x)\,(25{,}000)^{1/2}}$$

$$870 = \frac{5230(1000/25000)^{1/2}\,x}{(100+x)}$$

$$\text{or} \quad (100+x) = \frac{5230}{870 \times 5}\,x = 1.2\,x$$

then $.2x = 100$, or $x = 500$ ft.

The weight of charge is still expressed in terms of Δ. If we assume $\Delta = .2$,[1] then

---

[1] Density of loading for solid propellants varies between .4 and .7 for Naval guns. Whether such high densities of loading could be realized for liquids is not known for our purpose the values .2 and .3 are chosen to show the effect of variation of this parameter.

$$\bar{W} = \frac{1000}{(.2)^{.24}} = \frac{1000}{.68} = 1470 \text{ lbs.}$$ (approximately 16.5 cu.ft. or 130 gallons)

However, if $\Delta = .3$

$$\bar{W} = 1270 \text{ lbs.}$$

This shows the significance of the "density of loading" in determining the propellant charge. In what manner the injection rate is related to this solid propellant parameter is an important phase to be studied.

One more calculation will be made in order to estimate the time scale for injection. How long will the projectile be in the gun after it starts its travel? Expressing equation 1) as

$$\frac{dx}{dt} = v = \frac{ax}{b+x} = \frac{a}{b/x + 1}$$

and integrating over the distance traveled, 500 feet,

$$1/a \int_{1}^{500} (b/x + 1)dx = t$$

$$1/a \quad \left[b \ln x + x\right]_{1}^{500} = t_1$$

gives

$$\frac{620 + 500}{a} = t_1$$

Evaluating a, for $\Delta = .3$

$$a = 5230\ (1270/25{,}000)^{1/2}\ .3^{.12}$$

$$= 5230 \times .225 \times .865 = 1020$$

Therefore

$$t_1 = \frac{1100}{1020} = 1.1 \text{ seconds}$$

Note that x was evaluated from 1 to 500 feet since the Le Duc formula obviously does not describe the velocity initially. This can be seen by setting $x = 0$ in the acceleration equation 3)

$$\alpha = \frac{a^2bx}{(b+x)^3}$$

giving

$$\alpha = 0 \ .$$

Since the pressure is proportional to the acceleration, this indicates that the simple Le Duc formula does not give the correct initial pressure (when $x = o$). On the time scale the pressure and velocity curves do not have the same origin. Therefore, the time, t_1 , computed is a rough approximation giving us only the correct order of magnitude.

Now let us look at another set of specifications.

Specifications B

Gross weight to be accelerated	25,000 lbs.
End speed	104 knots
Accelerated run	150 feet
Maximum acceleration	3.5 g.
Maximum pressure	2000-4000 p.s.i.
Cylinder diameter	7"

Maximum acceleration is to be

$$3.5\ g = 3.5 \times 32.2 = 112\ \text{ft/sec}^2$$

which will occur at $x = b/2$. From the acceleration equation 3)

$$112 = \frac{4a^2}{27b} = \frac{4(5230)^2 w\ \Delta^{.24}}{27b \times 25{,}000}$$

or

$$w = \frac{112 \times 27 \times 25{,}000}{4 \times (5230)^2}\ \frac{b}{\Delta^{.24}}$$

$$\bar{w} = .69\ \frac{b}{\Delta^{.24}}$$

Also using equation 5)

$$p = \frac{wa^2}{6gAb} = \frac{\cancel{w}\ (5230)^2}{6gAb\ \cancel{w}}\ \bar{w}\ \Delta^{.24}$$

$$= \frac{(5230)\quad .69}{6g\quad 12.25\,\pi} = 2500\ \text{p.s.i.}$$

The maximum pressure is within specifications, so we proceed.

$$v_e = 104 \text{ knots} = 104 \times \frac{10}{6} = 173 \text{ ft/sec.}$$

and x_e is given as 150 ft.

From the velocity equation 1)

$$173 = \frac{a \times 150}{b + 150} = \frac{5230(\bar{w}/w)^{1/2} \ \Delta^{.12} \ \times 150}{(b + 150)}$$

or

$$(b + 150) = \frac{5230 \times \Delta^{.12} \ (\bar{w})^{1/2} \ \times 150}{173 \times 158}$$

$$= 28.7 \, \Delta^{.12} \ w^{1/2}$$

but from the acceleration calculation

$$\bar{w}^{1/2} \, \Delta^{.12} = (.69b)^{1/2}$$

then

$$b + 150 = 28.7 \, (.69b)^{1/2}.$$

This equation has no real solution for b. Why is this true? Returning to the specifications, if the maximum pressure were held constant throughout the firing, we would have a constant acceleration (theoretical) of

$$a = \frac{4000 \times 38.5 \times g}{25,000}$$

$$= 1.55g = 50 \text{ ft/sec.}$$

However, to attain a velocity of 173 ft/sec within 150 ft. would require a constant acceleration computed as follows:

$$v = at, \qquad t = \frac{v}{a}$$

and

$$x = \frac{1}{2}at^2 = \frac{1}{2}\,\frac{v^2}{a}$$

or

$$a = \frac{(173)^2}{300} = 100 \text{ ft/sec}^2$$

We conclude that the specifications are inconsistent. They must allow higher pressure, a larger cylinder, or a longer travel in order to attain the desired end velocity. These specifications were included to indicate that complications may arise before the ballistics are even applied. These specifications were undoubtedly laid down for an aircraft catapult where maximum acceleration must be low and length of run short. The corrected specifications would undoubtedly allow a larger cylinder diameter.

However, this would not remove the difficulty indicated when we could not get a solution for b. The specifications clearly require that an average acceleration very close to the maximum allowable must be used in order to acquire the end velocity within the specified distance. This means that the pressure must be held very close to the maximum also. The Le Duc formulas are not applicable to conditions of this sort. The equation relating velocity and displacement under these conditions is

$$v = k x^{1/2}$$

where

$$k = \sqrt{\frac{2gP A}{W}} = \sqrt{2gA}\,(P/W)^{1/2} = \text{constant}$$

Here W, the total weight accelerated, is the weight of the projectile plus the effective weight of the powder gases. The powder gases are increasing hence the pressure must increase in order to keep the ratio of pressure to total weight constant. Thus the maximum pressure will occur when the projectile is at the muzzle of the gun (or catapult). This is not the condition desired in high pressure guns since no expansion work is done and the gun would be very inefficient.

Now we will look at the specifications of an outdated Naval gun and try our Le Duc ballistic formulas with them.

Specifications C

Length of travel	241 inches
Muzzle velocity	2500 ft/sec
Diameter of bore	6 inches
Weight of projectile	130 lbs.
Maximum Pressure	18.5 tons/in^2 ⁽¹⁾

The solid propellant charge was 37 pounds. What weight of 90% H_2O_2 will be required?

Equation 1)

$$v = \frac{ax}{b+x} = \frac{a \times 20}{b + 20} = 2500$$

then $20a = 2500\ (b + 20)$

$a = 125b + 2500$

Also equation 6)

$$P_{max} = 41{,}500 = \frac{130a^2}{6 \times 32.2 \times 9\ b}$$

or

$$b = \frac{a^2}{1.74 \times 10^6}$$

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(1) Long tons are used for Naval ordnance pressure measurements, 2240 lbs/ton.

Solving the two equations in a and b for a, gives

$$a^2 - 1.4 \times 10^4 a + 34 \times 10^6 = 0$$

and $a = .32 \times 10^4$

Also

$$a = 5230 \, (\bar{w}/130)^{1/2} \, \Delta^{.12} = .32 \times 10^4$$

or $$(\bar{w}/130)^{1/2} = \frac{(.32 \times 10^4)}{5230} \, \frac{1}{\Delta^{.12}}$$

then $$\bar{w} = 130 \times .36 \times \frac{1}{\Delta^{.24}}$$

$$= \frac{47}{\Delta^{.24}}$$

If $\Delta = .2$, $\bar{w} = 47 \times 1.47 = 69$ pounds

If $\Delta = .3$, $\bar{w} = 47 \times 1.34 = 63$ pounds

If Δ1) $= .7$, $\bar{w} = 47 \times 1.09 = 51$ pounds

These calculations indicate that about twice the weight of propellant would be required using H_2O_2. instead of the smokeless powder charge. The relative performance is probably not as low as calculated here because the empirical percentage figure for smokeless powder was used to convert the available energy of the H_2O_2 to useful

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1) See note page 24.

energy and the same procedure was used to convert the theoretical pressure to guage pressure for H_2O_2. However, a more correct comparison can not be made since empirical data for the liquid propellant are non-existent.

Part III Conclusions

There is basically no reason why a gun propellant should be either liquid or solid. Solid propellants have been developed to a high degree of perfection because they offer a convenient way of controlling the rate of gas evolution through grain design.

Although the solid propellants are satisfactory for many gunnery applications they impose definite restrictions on ammunition handling and gun performance. The advantages to be looked for by using the liquid propellants are

1. Better gun efficiency at super velocities and less erosion.
2. Fewer men required to operate a battery.
3. Greater adaptability through the possibility of varying injection rate and amount.

The main disadvantage forseen is one of requiring more complicated mechanical devices.

It is difficult to evaluate the performance of the liquid propellant until a large amount of basic research has been performed. This basic research must be done in chemistry, physics, and engineering design.

The tactical requirements must be kept in mind as the research goes forward in order to aim the coordinated efforts of research groups in the desired, practical direction.

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